EFFECTS OF HOT AND COLD ENVIRONMENTS ON MILITARY PERFORMANCE

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I. Introduction and Overview

Survival and adjustment to extreme weather conditions have always been major problems for people living in hot and cold regions of the world; and, to a lesser degree in temperate regions, as well. Human physical structure and physiological characteristics provide little natural protection from the elements; thus, our only means of dealing with extreme climates has been to invent protective devices such as clothing, shelter structures, and reliable heating and cooling systems. Progress along these lines was slow for many centuries until the comparatively recent development in the eighteenth century of temperature measurement devices; and subsequently, accurate conceptualizations of the mechanisms of heat transfer. While dry-bulb and wet-bulb temperatures today are still the most familiar indices of the thermal environment, a better understanding of the interaction of temperature, humidity, and windspeed has led to more complex concepts, such as the wind chill index ~~proposed by Siple and Passel in 1945~~ and the wet-bulb globe temperature (WBGT). ~~developed by Yaglou and Minard in 1957.~~ The wind chill index was devised to express the cooling effect of wind velocity in the thermal process, and the WBGT was developed for the U.S. Armed Forces to determine endurable limits of heat exposure. An even more recent development is the 'Botsball' (Botsford, 1971), which provides a measure of wet globe temperature (WGT). Although Ciriello and Snook (1977) showed that this measure is highly correlated with WBGT values taken under the same radiation, humidity, and air movement conditions, Matthew, Hubbard, Szlyk, Armstrong, and Kerstein (1987) indicate that it may seriously underestimate the WBGT, particularly at low relative humidity and higher wind speeds. Despite these limitations, the Botsball avoids the fragility of glass thermometers, and in this respect is well suited for the military in field operations and for similar situations involving rough use. A different approach to thermal measurement called the operative temperature index, originated at the J. B. Pierce Laboratory of Hygiene by Winslow, Herrington and Gagge in 1938, was developed to assess the thermal exchange between man and the environment and to reflect thermal stress through the amount of heat flow. This index was developed further in 1955 by Belding and Hatch to evaluate high levels of heat exposure in industrial settings.

Along with such physical measures of environmental control, our understanding of subjective reactions to environmental exposure has also improved. In the 1920s, the American Society of Heating and Ventilation Engineers (later renamed the American Society of Heating, Radiation, and Air Conditioning Engineers, or ASHRAE), developed guidance for the design of heating systems. Out of this came the development of the effective temperature scale (ETS) by Houghten and Yaglou in 1923, based on subjective matching by raters of various experienced combinations of ambient temperatures, humidity levels, and air motion rates, to determine those combinations which produced equivalent feelings of personal comfort. See Fox (1965) for an excellent review of the development of thermal measurement.

II. Theoretical considerations

a. Bodily reactions and mechanisms in heat and cold exposure

Thermal stimulation is detected through the action of specialized sensory nerve processes embedded in the skin, adrenal medulla, hypothalamus, and other internal tissues. However, the density and distribution of thermal receptors in the deep skin tissues has not been established conclusively

(Hensel,1973), although it is clear that both their density and distribution vary for different skin areas of the body. Hensel and Bowman (1960) found specific receptors for cold in human skin, but could not locate warmth receptors. Iggo (1969) and Hensel (1970) reported that 'warm' receptors generate nerve potentials with positive coefficients, whereas 'cold' receptors produce negative coefficients. They found also that both kinds of receptors show a relatively constant rate of potential discharge at static temperatures within their thermal range of activity, and that they display an increased rate of discharge for changing temperatures proportionate to the rate of change. Receptors for both warmth and cold exist in human skin and probably take the form of free nerve endings. Although mechanoreceptors (tactual, pressure, etc.) produce virtually no thermal reaction, Hahn (1974) reported that some mechanoreceptors are responsive to cooling.

Neural discharges generated by thermal stimuli follow their associated afferent nerve pathways to join dorsal nerve trunks in the spinal cord reaching the anterior hypothalamus, a brain center thought to be active in temperature monitoring and control (Chowers and Bligh, 1976). The sensory coding for thermal response is not well understood. Under steady-state temperature conditions, both warmth and cold receptors habituate rapidly. Temperature sensation depends also on deep-body sensors outside the nervous system (Goltz and Edwards, 1896). See Elizondo (1977) for a concise review of the role of deep-body sensors in thermoregulation.

b. Theoretical basis for heat and cold effects

The general process of thermoregulation is considered to be based on the first law of thermodynamics (Mitchell, 1977), by which:

$$S = M + W + K + R + C + E$$

In this equation, the rate of heat storage (S) includes the metabolic rate (M) combined with the physical work rate (W), and with the rate of heat exchange of the individual with his surroundings through conduction (K), radiation (R), convection (C) and evaporation (E). Conservation and dissipation of body heat are accomplished by a variety of physiological mechanisms controlled by the anterior hypothalamus through its connection with the autonomic nervous system (Cabanac, 1975). Heat dissipation is accomplished by sweating and by dilation of the peripheral blood vessels which allows increased amounts of blood from the warmer core of the body to be shunted towards the body surface for cooling by radiation, convection, conduction and/or evaporation. Heat conservation is maintained through shivering, and through constriction of the peripheral blood vessels which confines blood to the warmer core of the body; and to a lesser extent, by the erection of hair follicles. The efficiency of both of these mechanisms is largely governed by the temperature, humidity, and rate of air movement of the surrounding environment.

Advances in neuroendocrinology have led to a greater understanding of the interaction of the anterior hypothalamus and adrenal medulla in thermoregulation. Robertshaw (1977) proposed a hypothetical model of thermoregulatory action in which the anterior hypothalamus is assumed to have two primary modes of control: through its influence on the sympathetic pathways of the autonomic nervous system, and through its ability to control secretion of catecholamines (epinephrine and norepinephrine) by the adrenal medulla directly into the circulating blood stream. Hormones of the adrenal medulla are known to strongly affect metabolism, and to cause increases in circulating free fatty acids and glucose, which are directly involved in mechanisms of thermal adjustment. Catecholamines also have some slight local effects on thermal receptor mechanisms at their tissue sites.

Satinoff (1978) proposed an alternative concept to the anterior hypothalamus as a single central neural integrator of body temperature. This conception assumes individual integrators for separate thermoregulatory responses, that are presumed to be located at various levels of the nervous system rather than at a single site. Since they are also assumed to function interactively, facilitation and inhibition among the levels can be achieved. This model provides for system-oriented and much more sensitive thermoregulatory action, and is more in line with recent physiological research findings.

Closely related to physiological thermoregulation is a general adaptive reaction to chronic cold or heat exposure termed 'acclimatization'. The processes involved in adaptation to heat differ considerably from those for cold, and are too complex for review here. See Fox (1965, pp. 64-76) for a review of the heat adaptation process; also, see Carlson and Hsieh (1965), and Fox (1967), for cold. Basically, heat acclimatization produces a lesser increase in heart rate during physical work, lowered skin and core temperature, a higher sweat rate, and reduced subjective feelings of discomfort. The responses involved in cold acclimatization are less clear. Some observed changes are: an elevated resting metabolic rate, an increased ratio of lean body mass to total body weight, and elevated temperatures of both the overall skin and the extremities, although these latter may be related to the rate of metabolic heat production. Increased time of onset of shivering and lowered metabolic heat production in winter compared to summer have also been reported (Davis, 1961a,b; Davis and Johnston, 1961).

III. Effects of heat and cold on behavior and performance

Understanding the physical, biological, and physiological aspects of human response to climate is based in large part on an increasing ability to precisely measure the physical environment, and to accurately define physiological and neurosensory functioning. However, it has been more difficult to establish well-defined relationships between climatic conditions and psychological performance. Even today, it is still a major problem to accurately predict the capabilities of both individuals and groups to perform their jobs under given climatic conditions.

The effects of climate on human performance have been studied for only about 70 years (Auliciems, 1973), beginning with early field studies of mine workers' performance (Orenstein and Ireland, 1922; Bedford and Warner, 1931). Although these early studies were only simple chronicles of behavior changes and differences in productivity, they pointed up the need for better control of confounding factors, and also led to the realization that psychological performance decrements and critical changes in physiological states do not necessarily occur together; in fact, psychological changes often precede physiological deterioration. This insight spawned a period of 'thermal stress' research to identify psychological 'breaking points' in performance rather than changes in physiological processes, beginning with the work of Mackworth (1945, 1946a,b), Pepler (1953a-g), and Viteles and Smith (1946), and continuing to the present. Studies involving extreme climates generally have been called 'thermal stress' research, while those dealing with more moderate conditions have been called 'subjective comfort' studies. A major difficulty here is that both involve different combinations of temperature, humidity, wind speed, and exposure time; and in practical terms, two hours of thermal stress in one study may be no worse for performance than 6 hours of a moderate temperature in another study. Also, the range and variation of climatic stressors used by investigators makes it difficult to make broad generalizations about their effects on psychological performance.

The advent of World War II created a sudden pressing demand by the military for more information to assess impairment levels and performance capabilities of troops exposed to stressful climatic conditions. The emphasis was to determine average performance changes for large numbers of troops, rather than to study variations among individuals, and attention focused on tasks with military relevance, such as vigilance, reaction time, tracking, cognition, and perception. These research strategies largely set the trends of climatic stress research following the war, and up to the present time.

Despite difficulties of interpretation due mainly to differences among testing conditions and exposure periods, as well as small subject groups, the major findings in heat and cold research over the last 40 years are reviewed in depth by Kobrick and Fine (1983). Tables 1 and 2 are an abbreviated updated version of their analysis summarizing what we know today about effects of heat and cold stress on psychological performance. These tables provide condensed guidance data on performance under climatic stress; for more complete information, see the sources listed in the Reference section.

Place Tables 1 and 2 about here.

Generalizing from the Tables about the effects of heat or cold on performance is difficult; however, some reasonable conclusions can be drawn. With respect to heat, vigilance tasks appear to become impaired above 90°F (32°C) and below 85°F (29°C) with best performance at or about 85°F/63%

relative humidity. Based on several studies, manual tracking also becomes somewhat degraded at or above 85°F (29°C) but differences in exposure periods create a complication. Although reaction time, sensation, and psychomotor performance each have been extensively studied, results indicate impairment, improvement and no changes of performance in the heat. Thus, although these categories of performance are crucially important to the military, the exact psychological tasks which are likely to be impaired during severe climatic exposures still cannot be stated specifically. Performance will certainly vary widely among different individuals. Impairment of various types of cognitive tasks for exposures above 100°F (38°C) have been reported, but again no change and even improved performance have also been observed.

Although much less research has been done on the effects of cold, the impairments noted generally seem to be related to loss of manipulative ability (e.g., Enander, 1984). Psychomotor tasks tend to be affected significantly at or below temperatures of 20°F (-7°C). Reduced sensory sensitivity has been reported for somewhat higher temperatures around 32°F (0°C), but this conclusion is based on one study. However, a very significant finding is the repeated observation of impaired manual dexterity at hand skin temperatures around 55°F (12.7°C). Although the relationship between hand skin temperature, whole body temperature, and rate of cooling is very complex (Kiess & Lockhart, 1970; Lockhart, 1966, 1968; Lockhart, Kiess, & Clegg, 1975), it seems clear that temperatures below this value indicate a stage at which finger joints stiffen, skin receptors become less responsive, and vasoconstriction of the peripheral blood vessels reduces or shuts off blood supply. Thus, mechanical and manipulative capabilities are impaired, and the ability of the hand to rewarm is reduced or virtually eliminated.

Studies of visual reaction time have shown no effects due to cold, but one vigilance study (Allan, Marcus, and Saxton, 1974) and one sensory study (Russell, 1957) showed decrements below 32°F (0°C). No firm conclusions can be drawn about the effects of cold on categories of tasks other than those involving manipulative skills and manual dexterity. The effect of humidity on performance in the cold has not been studied, but people typically seem to feel that wet-cold is much more uncomfortable and penetrating than dry-cold; hence, that wet-cold is more debilitating than dry-cold, whether or not it really is. Certainly, if clothing and handwear become wet in a cold environment, thermal insulation properties are compromised and body heat loss ensues.

There are some indications that heat and cold produce characteristically different time progressions of impairment to psychological performance. A few studies of heat effects note an initial facilitation of performance, followed later by a gradual continuing deterioration. An example of this trend can be found in a study by Fine and Kobrick (1978) involving the continued performance of several rational-cognitive tasks used by artillery fire control teams over a 6-hour period of exposure to very hot-humid conditions (95°F/88%RH). Performance of most of the tasks improved over the first hour, and then gradually deteriorated. This trend may be due hypothetically to heat effects causing an initial enhancement of neural conductivity and cortical processing, to be overcome later by the overall debilitating physiological effects of extreme heat. However, this theory has never been tested.

The effects of cold generally seem to produce an increasing progressive impairment of performance with no significant recovery until major rewarming occurs. If moderate rewarming is possible, such as coming into a heated shelter briefly, performance may partially recover, but usually not to normalcy. This process results in a downward step function interspersed with periodic short plateaus, ending in complete incapacitation if total rewarming does not occur.

Another significant difference between the direct effects of heat and cold on performance is the localized impairment of the extremities by cold exposure. The hands and feet can be numb and stiff while the central body remains warm and functional. Such behavioral effects are not seen in heat exposure.

Motivational and attitudinal factors for exposure to extreme temperatures are also significant, if not equally as important to performance as the direct effects of heat and cold themselves. Records and anecdotes of the noted military historian, S. L. A. Marshall (1947) include numerous instances of men ceasing to function in both extreme heat and deep cold, although they were physically unharmed at the time. In the arctic, a typical reaction to prolonged cold exposure termed "huddling in", is characterized by inactivity and a drawn-in posture, probably stemming from an attempt to conserve core body heat. However, this reaction leads instead to a reduction or cessation of activity, which in turn results in further body cooling. In arctic communities, a common behavior syndrome called "cabin fever" occurs during the arctic winter, wherein inhabitants isolate themselves from contact with others for long periods, and become practically dormant, resembling in some respects the hibernation phenomenon in lower animals. Tropic regions are also known to sap the will and motivation to perform, especially routine tasks, even though adequate rations, water and appropriate clothing and equipment may be available. Although we know these as typical reaction patterns to heat and cold, it is difficult to document and quantify such behavior objectively (Johnson, Branch, & McMenemy, 1988), and thus, good analytical data in these areas is practically non-existent.

While considerable research has been done on subjective comfort (Griffiths and Boyce,1971; Langkilde, Alexandersen, Wyon, and Fanger, 1973; Wyon, 1973, 1974; Wyon, Fanger, Olesen, and Pedersen, 1975; Wyon, Anderson, and Lundquist, 1979), generally it is difficult to interpret the results, because the environmental controls were limited and the performance data were obtained through unmatched samples of real-life working situations, such as school children doing class-work. Even so, there is an indication of possible impaired performance with increased discomfort (Kiess & Lockhart, 1970). Despite the limited value of such data for military interests, one must note the potential importance of this research area, because it involves climatic conditions found in typical daily living. However, personal comfort is a highly individualistic issue, and will show great variation in its relationship to optimum performance among various personnel. On a common-sense level, one should certainly expect discomfort to have a negative influence on general performance, if only from its effect as a distracting element.

Another consideration is the occurrence of cyclical patterns in human biological processes, and how these may relate to behavioral performance. One such pattern is the diurnal rhythmic sinusoidal rise and fall of core body temperature, characterized by a circadian lull around 0300 - 0600 hours. First noted by Marsh (1906), such patterns were later corroborated by Kleitman (Kleitman, 1933; Kleitman and Doktorsky, 1933; Kleitman, Teitelbaum, and Feiveson, 1938), who noted an association between body temperature and task performance on code transcription, arithmetic operations, mirror-drawing, and reaction time. Kleitman postulated a chemical basis for the relationship, in line with Francois' (1927) previous observation that body temperature and time perception were related. These views corresponded to Hoagland's later concept of a chemical clock (1933), based on the notion that the perception of time varies with internal body temperature and brain metabolism. Later studies (Bell, 1965, 1966; Fox, Bradbury, Hampton, and Legg, 1967; Kleber, Lhamon, and Goldstone, 1963) have tended to support this concept, but large differences among individual subjects have made overall generalizations difficult.

In a special category are heat and cold effects found in studies involving artificial manipulation of subjects' core temperatures by thermal suits, water immersion, and other such techniques. Although many of these findings are no doubt significant, core temperatures of subjects cannot be readily equated with natural ambient environmental conditions which would produce the same internal thermal effects, and therefore are hard to relate to performance under climatic extremes. Such transformations are also difficult to generalize from, due to the wide variation in temperature response among individuals. Therefore, although core temperature manipulation is potentially a highly valuable approach, this chapter does not include such findings, since the focus is on empirical performance effects of climate.

Another group of reports concerns effects of cold combined with prolonged isolation, such as sojourns in the Antarctic and at isolated military duty stations (Gunderson and Nelson, 1963; Nelson and Gunderson, 1963; Gunderson, 1966). Although valuable in itself, this literature cannot be used to interpret the direct effects of cold alone on general operational capability or on specific performance tasks, because of the concurrent interaction with effects of isolation. Recent findings concerning the potential effects of restriction of ambient light on behavior create a further problem in interpreting the available data on performance under prolonged cold because of the prevailing arctic night in cold regions of the world. Even so, these articles show a general consensus that given good health, adequate food, clothing and shelter, and having positive motivation, individuals can cope with prolonged arctic and antarctic conditions quite well.

A fundamental consideration in assessing climatic effects on performance is acclimatization, or the development of better physiological tolerance to environmental extremes through continued exposure. This concept implies that acclimatized people should perform better on psychological tasks under environmental stress than unacclimatized people would, but this assumption has not been conclusively tested, although physiological effects of acclimatization are well known. Much of the published psychological research on climatic effects has used unacclimatized people, due undoubtedly to the difficulties and lengthy times involved in developing the required states of acclimatization in suitable numbers of test subjects. The natural influence of the prevailing season of the year at the time of the study may be another complicating factor. Nevertheless, acclimatization has only infrequently been used as a systematic experimental variable in studies of performance involving climate. In fact, the prevailing climate or even the season of the year at the time of data collection is rarely stated in research reports. This seems to suggest that most investigators are not very cognizant of the potential effects of sustained climatic exposure, or do not have the means available to deal with the issue in their research. At any rate, in our opinion it seems clear that acclimatized people perform better both in hot and cold conditions than do unacclimatized people. This may be due to acquiring greater proficiency through actual exposure to climatic extremes; however, it may also be due to increased expectations of success and improved motivation through experience with heat or cold. These aspects of psychological performance in heat and cold have received little attention (Johnson, Branch and McMenemy, 1988).

IV. Practical applications and military considerations

Considering the discussion above in an overall sense, it is clear that we need to know a great deal more about human performance under climatic extremes. Nevertheless, a number of practical recommendations and useful guidelines can be drawn from the research findings and practical experience that is already available on environmental effects. Many of the recommendations in this section are also drawn from the authors' personal experience in research on effects of climatic extremes.

a. Performance in the heat

(1) Heat affects the performance of different types of tasks to varying degrees. Since heat has a cumulative blunting effect, continuous tasks of low demand, tasks with relatively low arousal value and those of a boring and repetitive nature will tend to be affected most (e.g., vigilance, low-activity sentry or surveillance duty, routine watchkeeping, etc.). Interesting tasks with fairly frequent occurrence rates will tend to be less affected by heat.

(2) Heat affects the performance of different people according to their skill level. Those who are well trained at their jobs are better able to withstand ambient heat (Mackworth, 1950). A skilled individual requires less effort to complete a given task than does an unskilled individual. As a general rule, the better trained the soldier, sailor or airman, the better the

performance under ambient heat conditions.

(3) Tasks to be performed in the heat, particularly those of a crucial nature, should be initially learned and practiced in the heat, since the conditions under which they are performed are altered by heat. The typical bodily reactions to heat exposure can create performance conditions which are quite different from those for the same task done under cool conditions. For example, sweat running into the eyes can blur vision and create interruptions caused by the need to the wipe face and hands. Plastic controls can become slippery due to sweaty hands. Even the physical properties of materials (e.g., elasticity, stickiness, expansion) involved in a task can change when the materials are heated. Eyepieces and headsets can become uncomfortable or painfully hot, as well as physically unstable on the head due to sweating. In the past, we have tended to think of such effects on performance in the heat as "artifact" and not worthy of serious investigation. Hancock (1984) referred to such effects as "coarse grained actions" which are often the immediate cause of serious decrements in performance and, consequently, should be the focus of serious investigation. Mackworth (1950) suggested that failure to find an obvious cause (coarse grained action) for a performance decrement may mean that other less obvious correlates of performance (e.g., core temperature) are less than satisfactory objects for investigation.

(4) On a perceptual level, hot environments can create mirages, visual distortions, and optical illusions due to heat shimmer and glare, which in turn result in reduced or inaccurate performance of visual tasks. There are even data to show that visual acuity may become impaired in hot environments (Hohnsbein, Piekarski, Kampmann, and Noack, 1984). The occurrence of these phenomena further justifies the recommendation that military personnel train

in a hot environment when preparing for work in the heat. Similarly, it is important that the training be in an environment most similar to the operational environment with respect to terrain so that personnel will become familiar with possible visual effects.

(5) In some instances, ambient heat creates very warm surfaces which are uncomfortable, difficult, or painful to handle (Stoll, Chianta, & Piergallini, 1982), and thus retard performance. Metal surfaces of equipment and vehicles which can be contacted normally in cool conditions can become unbearably hot or produce actual skin burns when contacted out in the open in the sun (Stoll, Chianta, & Piergallini, 1979). Thus, heat by itself can preclude or drastically curtail the performance of many operational tasks for mechanical reasons totally unrelated to physiological heat tolerance.

(6) The operator's personal equipment is another important factor in considering the effects of heat on performance. Gloves and masks are probably the greatest concern, because by themselves they mechanically obstruct the major sensory and information-gathering zones of the body (Johnson & Sleeper, 1986). However, in the heat they also generate another set of problem conditions, particularly when they are part of impermeable or encapsulating ensembles, such as chemical protective gear. Trapped moisture inside the suit condenses on eyepieces and viewing ports of face masks, further restricting vision beyond the occlusion of the mask itself. Gloves become slippery inside and slide against the hands, making the sensory impairment created by the rubber glove material even worse. Cloth glove liners become soaked and bunch up at finger joints or slip down on the hands and wad up. In effect, the trapped moisture inside the impermeable suit creates a micro-climate like that of a tropical rain-forest, creating ergonomic problems beyond those due

to physiological heat load. Finally, the hands and feet swell due to heat-related tissue edema, reducing joint motility and manual dexterity. We have seen hands swollen to half-again their normal size under such heat conditions.

(7) The effects of heat on performance may be of particular concern in operation of aircraft and armored vehicles, due to the heat build-up within closed crew compartments. Temperatures within helicopter crew enclosures can reach 135^{o}F (57.3^{o}C) (Breckenridge and Levell, 1970). Crew compartments of tanks and other armored ground vehicles can surely be expected to develop similar temperature levels, particularly when sealed for chemical, biological or radiological (CBR) operations in a desert environment. Furthermore, such thermal stress levels can only be expected to intensify when personnel are required to wear chemical protective clothing, especially at the most extreme (MOPP-IV) level of encapsulation in vehicles which are closed but still not equipped with positive pressure or CBR-sealed systems. Although such excessive heat levels mandate the use of artificial cooling, circumstances can easily arise where such equipment is inoperative or unavailable. Research on simulated helicopter operations in the heat showed that normal flight operations and related flying tasks were unaffected at an ambient temperature of 29.05^{o}C WBGT (Hamilton, Simmons, and Kimball, 1982). However, cognitive skills (decision making, judgment capability), mood states and ability to react and to deal with error situations showed some impairment. Other research on simulated helicopter operations in hot conditions (Knox, Nagel, Hamilton, Olazabel, and Kimball, 1982; Mitchell, Knox, Edwards, Schrimsher, Siering, Stone, and Taylor, 1986; Moreland and Barnes, 1970) warn that cognitive and judgmental skills are a relevant concern, as well as a slowing of reaction speed and response time for complex behaviors. Other research on

simulated tank crew tasks in the heat (Rauch, Banderet, Tharion, Munro, Lussier, and Shukitt, 1986; Tharion, Rauch, Munro, Lussier, Banderet, and Shukitt, 1986; Toner, White, and Goldman, 1981) showed behavioral impairments and mood changes similar to those found for helicopter operations.

b. Performance in the cold

(1) Cold exposure primarily affects the psychomotor and manual dexterity aspects of task performance. These impairments are largely due to stiffening of the muscles, joints and possibly synovial joint fluids, resulting in a mechanical "locking up" of the biomechanical capabilities of the hands. Based on Gaydos (1958), Clark, (1961), and more recently, Bensel and Lockhart (1974), manual dexterity tasks are affected whenever the hands are cooled to a critical peripheral temperature (55°F (12.7°C) skin temperature, according to Clark). The crucial factor in maintaining dexterity, therefore, is hand temperature despite the temperature level of the rest of the body. However, the rate of development of low peripheral temperatures will certainly be influenced by the overall state of warmth of the individual and the rate at which cooling is achieved (e.g., Lockhart, 1968). At any rate, keeping the hands warm is essential for preserving operational capability.

(2) Loss of dexterity in the cold is accompanied also by reduction of tactile sensitivity, resulting in diminished feedback as to what the hands are doing. This may be compensated visually, but visual feedback obviously will not serve for tasks performed in the dark, or if the task components to be manipulated are hidden from sight (i.e., parts under a housing, etc.) It should also be remembered that sensitive tasks which must be done bare-handed may also involve cold-soaked components, which will cause further contact cooling in the very situation where sensitivity is essential. Consider the

ramifications of deactivating a mine-field in the cold.

(3) Local peripheral application of heat to the hands has been shown to be an effective remedy for maintaining manual capability in the cold (Lockhart & Kiess, 1971). As an example of this, reduced gunnery efficiency due to stiffening of the hands of aerial machine gunners standing at open bays in the cold slipstream could be significantly helped by installing a warm air or radiant heat source directed at the hands. Electrically heated handwear and footgear have been an effective remedy for pilots on long flights; however, this may not be a solution for ground troops because of the need for a power source.

(4) Much of the reduction of operational capability caused by cold conditions can be circumvented by different performance strategies than those used under normal circumstances. First, it must be recognized that tasks must be broken into shorter segments, interrupted by re-warming of the hands. Many manipulative tasks can be completed if operators can pause periodically either to go inside shelters or to don handwear for a period of time. Plastic coatings on knobs and controls can help a great deal to improve manipulability, and to avoid contact freezing of skin to metal surfaces. Ergonomic re-design or enlargement of critical controls may be possible, so as to allow manipulation while wearing gloves. As mentioned above for hot conditions, important tasks to be performed in the cold should be learned and practiced in the cold.

(5) The properties of physical materials to be used in the cold are an important consideration. Hydraulic-based tracking systems of weapons may have perfect feedback properties in temperate conditions, but in wet-cold or the arctic will develop different hysteresis levels, and throw off the operator's

normal tracking performance. At worst, the system can completely lock up. Patch-cords, cabling and hose made of plastic or rubber may be perfectly suitable for warm or hot conditions, but in the cold will be impossible to unreel or re-coil. In extreme cold, such materials can crack or snap off, creating electrical shorts or other hazards. Many of these conditions which result in serious performance limitations or even disastrous operational problems can be reduced by careful re-engineering of equipment to be used in the cold. However, the military-standard equipment now in the field will be present for some time to come, and as such will continue to create performance problems for troops in cold operations.

(6) Water sources and containers may present an extremely important problem in arctic conditions. Any water container is vulnerable to freezing and then bursting. Drinking water supplies are a particularly serious matter, considering the additional possibility of contamination. The physical problems connected with disruptions of water supply can then contribute to increased dehydration of troops, a familiar problem in arctic operations.

(7) The skills and techniques involved in medical field aid and evacuation procedures involve different problems in cold than in temperate or hot conditions. Plastic equipment, containers and tubing can become brittle or crack. Contents of syringes and infusion bags can freeze or change in viscosity. Casualty and evacuation bags have been improved for use in the cold, but still present manipulation problems involved in entrance and exit of the casualty.

(8) Another problem for manipulative performance is the effect upon the hands of re-warming to the point of sweating, followed by subsequent cooling. The moisture generated in sweating then deposits in handwear, and results in

accelerated cooling later on, with the additional potential hazard of frostbite due to wet mittens or gloves. The same problems exist for handwear which becomes wet for other reasons. In the alternative situation where personnel remove their handwear to cool down or dry off their hands, there is a considerable risk of desensitization of the hands or possible frostbite when the skin cools too quickly to be reacted to safely.

V. Discussion and Conclusion

The effects of heat and cold on human performance are often discussed as if cold and heat are two independent variables (albeit on the same temperature continuum) which are easily isolated, and to which the human test subject may be exposed with minimal interference from other factors, such as wind. While this may be true in the laboratory, it is clearly not true in the real world. In the real world of ambient heat, for example, people wear hats and other items of clothing to protect themselves from solar radiation. With sweating, the hat absorbs moisture and promotes efficient evaporative cooling of the head. Without a hat, and other items of clothing, sweat drips off the human body and evaporative cooling becomes less efficient. In the real world, people also behave in ways to protect themselves from environmental temperature extremes. That is, in hot climates people seek shade and work at night to avoid obvious sources of extreme heat. Nowhere is the effect of the real world more obvious than when we try to apply our laboratory findings to real cold weather situations. In the real world, a person will dress warmly, arrange his work schedule to avoid prolonged cold exposure (e.g., sharing of sentry duty), and change the way in which a task is carried out (e.g., use large tools to accommodate bulky gloves).

Laboratory findings are limited in generalizability, and we should always be aware of this limitation. Further research on the effects of heat and cold on human performance must involve serious consideration of the practical influences of the real world on the performance of military personnel. That is, we must be aware not only of basic research findings, but also of the environmental demands placed on personnel in the field. Our discussion of this topic has shown repeatedly that human performance is an outcome of a complex network of environmental variables (temperature, humidity, solar and ground raditiation, wind, ground conduction, etc.), individual human variables (metabolic heat production, training, experience, skill levels, motivation, etc.) and clothing and equipment variables (equipment radiation and conduction, clothing insulation, clothing bulk, fit of clothing and equipment to body parts, etc.). Because so many variables may play a role in influencing human performance, we must not be surprised at the complexity of results from research in this area. Also, we must not ignore the importance of some variables (e.g., clothing and equipment variables) by considering them "artifactual". Some of the most relevant factors influencing human performance may be these "artifactual" or "coarse-grained actions" to which we have only on occasion given proper attention.

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TABLE 1
SUMMARY OF EFFECTS OF AMBIENT HEAT ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. $^{\circ}$F	RH %	Time min.	Comments
A. Reaction Time				
Grether et al(1971)	72	Ambient	95	Possible decrement in choice
	120	Ambient	95	RT at 120°F
Lovingood et al(1967)	74	30	60,120,180	Improved simple RT 126°F
	126	30	60,120,180	
Ramsey et al(1975)	99	42	120	Possible increase in simple
	110	44	90	RT at 120°F
	120	47	45	
B. Sensory				
Hohnsbein et al	84	40	180	Visual acuity impaired at
(1984)	101	65	180	101°F and above
	122	10	180	
Russell(1957)	68	47	73	Best tactile sensitivity
	85	33	73	at 85°F
	103	30	73	
C. Vigilance				
Arees(1963)	55	40	80	Visual task; diff. temp/perf-
	75	40	80	ormance relationships among
	105	40	80	different Ss
Colquhoun(1969)	75	59	120	No diff in visual vigilance
	90	65	120	performance
	120	24	120	
Colquhoun & Goldman	75	41	120	0,10,20 or 30 min walk before
(1972)	103	68	120	visual vigilance test. No diff
Mackworth(1946a)	75	59	120	Visual search best at 85°;decre-
	85	63	120	ments occur above & below 85°F;
95 66 120	acclimatized Ss			
	105	69	120	
Mortagy & Ramsey	80	50	180	Visual vigilance; decrements
(1973)	92	50	180	at 102oF increasing with work
	102	50	180	level and work-rest ratio

TABLE 1 (continued)
SUMMARY OF EFFECTS OF AMBIENT HEAT ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	RH %	Time min.	Comments
C. Vigilance (cont.)				
Pepler(1958)	75	59	120	Decrements in visual vigilance
	90	65	120	above and below 90°F
	120	24	120	
Poulton & Edwards (1974b)	68	72	90	Visual vigilance; less correct
	100	74	90	detections at 100°F
Poulton et al (1974)	68	72	90	Auditory vigilance; less
	100	74	90	correct detections at 100°F
D. Psychomotor				
Lovingood et al(1967)	74	30	60,120,180	Better in aptitude classification
	126	30	60,120,180	and steadiness at 126°F
Mackworth(1945)	85	63	180	Poorer pointer alignment
	90	65	180	above 90°F
	95	66	180	
	100	68	180	
	105	69	180	
E. Tracking				
Grether et al(1971)	72	Ambient	95	No change in compensatory
	120	Ambient	95	tracking
Pepler(1953a)	75	59	160	Poorer pointer alignment at
	85	63	160	85°F, increased with higher
	93	66	160	temp.; acclimatized Ss
	100	68	160	
Pepler(1958) (study 3)	85	63	150	Best manual tracking at 90°F.
	90	65	150	Poorer manual tracking above
	95	67	150	and below 90°F;acclimatized Ss
	100	68	150	
Pepler(1959a)	116	70	30	Poorer pointer align. at 116°F
Pepler(1959b)	69	77	30	Poorer pointer align. at 100°F
	100	68	30	

TABLE 1 (continued)
SUMMARY OF EFFECTS OF AMBIENT HEAT ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	RH %	Time min.	Comments
E. Tracking (cont.)				
Pepler(1960)	69	77	40	Poorer pointer align. at 100°F
	100	68	40	
Russell(1957)	68	47	73	No diff. in tracking tasks
	85	33	73	
	103	30	73	
F. Concurrent tasks				
Bell(1978)	72	45	33	Primary task=pursuit rotor;
	84	45	33	second task=number processing
	95	45	33	Decrement in second task at 95°F
Dean & McGlothlen (1965)	70	40	20	Very short exposures; no diff
	80	41	20	in tracking, radar monitoring
	90	44	20	
	100	48	20	
	110	50	20	
Iampietro et al(1972)	77	45	50	Decrements in some simulated
	110	22	50	flight at 110°F and 140°F
	140	11	50	
Mackie & O'Hanlon (1976)	66		540	More steering adjustments, less
	90 (WBGT)		540	brightness discrim., more drive errors at 90°F
Provins & Bell(1970)	68	59	175	Training unstated; RT better
	104	72	175	then no change at 104°F; no diff in vigilance
G. Memory, Cognition, and Perception				
Bartlett & Gronow (1953)	60 to 70	--	60	No difference in perf. on
	80	61	60	a cognitive game
	90	65	60	
	100	68	60	
Fine & Kobrick(1978)	70	35	420	Improved perf. at 3rd hr.;
	95	88	420	sig. decrements thereafter

TABLE 1 (continued)
SUMMARY OF EFFECTS OF AMBIENT HEAT ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	RH %	Time min.	Comments
G. Memory, Cognition, and Perception (cont.)				
Fine et al(1960)	70	30	390	No diff. in perf. of anagram
	70	90	390	and auditory discrim. tasks
	95	28	390	
	95	89	390	
Grether et al(1971)	72	Ambient	95	No diff. in perf. on short-
	120	Ambient	95	term memory
Lovingood et al(1967)	74	30	60,120,180	Better mental arithmetic
	126	30	60,120,180	at 126°F
Mackworth(1946a)	85	63	180	Lower Morse code reception
	90	65	180	above 90°F; acclimatized Ss
	95	66	180	
	100	68	180	
	105	69	180	
Pepler(1959b)	69	77	50	Serial choice worse at 100°F
	100	68	50	
Pepler & Warner(1968)	62	45	180	Greater effort, errors and
	68	45	180	perf. in prog. learning above
	74	45	180	and below 80°F. Performance best
	80	45	180	at 80°F.
	86	45	180	
	92	45	180	
Poulton & Edwards	68	72	60	No change on 5-choice task
(1974a)	100	74		
Poulton et al(1974)	68	72	60	More gaps and errors on
	100	74	60	5-choice task at 100°F
Ramsey et al(1975)	99	42	120	Decrements in arithmetic
	110	44	90	task in heat
	120	47	45	
Reilly & Parker(1968)	75	40	360	Of 16 tasks, 6 better, 2 worse,
	100	42	360	8 same at 100°F

TABLE 1 (continued)
SUMMARY OF EFFECTS OF AMBIENT HEAT ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	RH %	Time min.	Comments
G. Memory, Cognition, and Perception (cont.)				
Wing & Touchstone (1965)	80	38	60	Poorer short-term memory at 120°F
	110	30	60	
	120	28	60	

TABLE 2
SUMMARY OF EFFECTS OF AMBIENT COLD ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	Time min.	Comments
A. Reaction Time			
Aiken(1957)	-4	36	No effect on learning RT task
	70	36	
Horvath & Freedman (1947)	-20	8-14 days	No diff. in discrim. RT
	-10 to -14	180	
	72	4 days	
B. Sensory			
Russell(1957)	14	73	Poorer kinesthetic and tactile sensitivity at 32°F or lower
	32	73	
	50	73	
	68	73	
C. Vigilance			
Angus et al(1979)	32 to 41	45	Poorer vigilance at -5 to -35°F
Allan et al(1974)	-22	Varied with hand skin temp.	Poorer perf. at 14°F and below
	-4		
	14		
	50		
D. Psychomotor			
Bensel & Lockhart (1974)	20	180	Poorer manual perf. at 20°F
	60	180	
Clark(1961)	10	Up to 60	Lower dexterity at hand skin temp of 55°F
	70		
Gaydos(1958)	45	Varied as to skin temp.	Lower dexterity at 50 to 55°F hand skin temp.
	75		
Gaydos & Dusek(1958)	15	Varied as to skin temp.	Lower dexterity as a function of hand skin temp.
	75		

TABLE 2 (continued)
SUMMARY OF EFFECTS OF AMBIENT COLD ON PSYCHOLOGICAL PERFORMANCE

Author(s)	Temp. °F	Time min.	Comments
D. Psychomotor (cont.)			
Horvath & Freedman (1947)	-20	8-14 days	Poorer gear assembly and transcription
	-10 to -14	180	
	72	4 days	
E. Tracking			
Russell(1957)	14	73	Poorer tracking at 32°F or lower
	32	73	
	50	73	
	68	73	